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Minimal flavor violation in the lepton sector of the Randall–Sundrum model

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ABSTRACT

We propose a realization of Minimal Flavor Violation in the lepton sector of the Randall–Sundrum model. With the MFV assumption, the only source of flavor violation are the $5D$ Yukawa couplings, and the usual two independent sources of flavor violation are related. In the limit of massless neutrinos, the bulk mass matrices and $5D$ Yukawa matrices are simultaneously diagonalized, and hence the absence of FCNCs. In the case of massive neutrinos, the contributions to FCNCs in the charged lepton sector are highly suppressed, due to the smallness of neutrino masses. In addition, the MFV assumption also allows suppressing one-loop charged current contributions to flavor changing processes by reducing the size of the Yukawa couplings, which is not possible in the generic anarchical case. We found that the first KK mass scale as low as ~ 3 TeV can be allowed. In both cases, we present a set of numerical results that give rise to realistic lepton masses and mixing angles. Mild hierarchy in the $5D$ Yukawa matrix of $\mathcal{O}(25)$ in our numerical example is required to be consistent with two large and one small mixing angles. This tuning could be improved by having a more thorough search of the parameter space.

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1. Introduction

The Randall–Sundrum (RS) model [1] is a solution to the gauge hierarchy problem based on non-factorizable geometry in a slice of AdS_5 space with warped background metric. By allowing the fermion and gauge fields to propagate in the bulk [2], the model can accommodate fermion mass hierarchy by localizing different fermions at different locations along the fifth dimension, while having all $5D$ Yukawa couplings to be $\mathcal{O}(1)$ [3,4]. It also gives rise to novel ways to generate small neutrino masses [3,5]. Realistic models based on bulk custodial symmetry [6] or large brane kinetic terms [7] have also been built, in which the first KK mass scale ~ 3 TeV is allowed by the electroweak precision data. The RS model with bulk fermions and gauge bosons has a rich flavor structure. There are two sources of flavor violation, the $5D$ Yukawa couplings and the bulk fermion mass terms, which can generate dangerous tree-level FCNCs mediated by the KK gauge bosons. Even though these processes are somewhat suppressed by the built-in RS GIM mechanism [8], constraints from the CP-violating parameter ϵ_K for $K^0-\bar{K}^0$ mixing still gives a stringent bound of 8 TeV with a generic flavor structure [9]. A detailed scanning of the parameter space has shown recently that the first KK gluon mass should be heavier than about 21 TeV for the generic anarchical case [10].

Lepton flavor violation (LFV) in various rare leptonic processes mediated by neutral KK gauge bosons also gives stringent constraints on the KK mass scale. LFV in the RS model has been studied before [11–13]. Even in the case of massless neutrinos, severe bound on the first KK mass scale already arises from FCNC-mediated processes in scenarios with generic anarchical $5D$ Yukawa couplings [13]. Moreover, there is a tension between loop induced processes, such as $\mu \rightarrow e\gamma$, and the tree-level flavor violating processes, such as $\mu-e$ conversion, since they depend on the $5D$ Yukawa coupling constants oppositely [13]. As a result, the allowed parameter space for the $5D$ Yukawa couplings is very restricted and it is not possible, in the generic anarchy case, to relax the bound on the KK mass scale by tuning the $5D$ Yukawa coupling constants.

Suppression of flavor violation with bulk and brane flavor symmetries has been studied [14]. In [15], the assumption of minimal flavor violation (MFV) [16] is applied to the quark sector of the RS model, which assumes that the $5D$ Yukawa couplings are the only source that breaks the global flavor symmetry and the bulk mass matrices are related to the $5D$ Yukawa couplings as dictated by the flavor symmetry. This thus provides an alignment between the two flavor violating sources that are otherwise independent in the general case.

In this Letter, we propose a realization of MFV in the lepton sector of the RS model. In the massless neutrino case, the $5D$ bulk mass matrices and $5D$ Yukawa matrices can be diagonal simultaneously. There are thus no leptonic FCNCs at tree level. In the presence of massive Dirac neutrinos, due to the MFV assumption, the FCNC contributions are controlled by one single parameter, ξ . In

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terestingly, small neutrino masses requires $\xi \lesssim 0.1$, leading to very suppressed FCNCs and thus allowing a light KK mass scale, making it possible to test the model at the collider [17]. Furthermore, MFV also alleviates the tension that exists in the generic anarchical case between the tree-level FCNCs and one-loop charged-current contributions to LFV processes. It allows the charged-current contributions to be suppressed by reducing the Yukawa couplings without increasing the tree-level FCNC contributions.

2. Minimal flavor violation in the lepton sector

Massless neutrino limit. With the MFV assumption, all flavor violation come from the 5D charged lepton Yukawa couplings Y_e . The relevant bulk mass matrices and the 5D Yukawa couplings are

$$\mathcal{L}_{5D}^{\text{lep}} \supset \bar{L} C_L L + \bar{e} C_e e + \bar{H} \bar{L} Y_e e. \quad (1)$$

To implement the MFV in the lepton sector, we assume the bulk mass matrices for the lepton doublets and singlets are aligned with the 5D Yukawa coupling Y_e as

$$C_L = b Y_e Y_e^\dagger, \quad C_e = a Y_e^\dagger Y_e, \quad (2)$$

where a and b are $\mathcal{O}(1)$ parameters.¹ With $U(3)_L \times U(3)_e$ global flavor symmetry, we can select a basis such that Y_e is in the diagonal form, \hat{Y}_e . In this basis, both bulk mass matrices $C_e = a \hat{Y}_e^\dagger \hat{Y}_e$ and $C_L = b \hat{Y}_e \hat{Y}_e^\dagger$ are diagonal and thus all leptonic flavor violation vanish. We comment that in the Randall–Sundrum framework, the Yukawa couplings can in general be of order $\mathcal{O}(1)$. In that case, there are large higher order corrections involving four and more Yukawa matrices to Eq. (2) in the expansion. Even though these higher order corrections will change the numerical fits to \hat{Y}_e , with massless neutrinos, the matrices C_L and C_e can still be diagonalized simultaneously. As a result, the tree-level FCNCs are still absent. From the numerical solutions given below, one sees that in order to obtain realistic lepton masses, the Yukawa couplings are all small compared to 1, and thus the expansion in Eq. (2) is justified.

We next show that the MFV assumption in Eq. (2) can indeed give rise to realistic charged lepton masses. In the brane Higgs case,² the charged lepton masses are given by $m_l \simeq v F_L Y_e F_e$, where $v = 174$ GeV, and F_L and F_e are the values of the zero-mode profiles on the TeV brane for the lepton doublets and singlets, respectively. The eigenvalues of F_L and F_e are given by

$$f_{L_i} = \sqrt{\frac{1 - 2c_{L_i}}{1 - \epsilon^{1-2c_{L_i}}}}, \quad f_{e_i} = \sqrt{\frac{1 - 2c_{e_i}}{1 - \epsilon^{1-2c_{e_i}}}} \quad (3)$$

where $\epsilon = e^{-\pi k r_c} \simeq 10^{-15}$ and c_{L_i} and c_{e_i} are the eigenvalues of the 5D bulk mass matrices C_L and C_e . As shown above, the matrices Y_e , C_L and C_e can be diagonal simultaneously due to the MFV assumption. In the diagonal basis, $Y_e = \text{diag}(Y_{e_1}, Y_{e_2}, Y_{e_3})$, $C_L = \text{diag}(b|Y_{e_1}|^2, b|Y_{e_2}|^2, b|Y_{e_3}|^2)$ and $C_e = \text{diag}(a|Y_{e_1}|^2, a|Y_{e_2}|^2, a|Y_{e_3}|^2)$. Without loss of generality, we choose $a = 1$ and $b = 1$. With the values of $Y_{e_1} \simeq 0.816$, $Y_{e_2} \simeq 0.759$ and $Y_{e_3} \simeq 0.720$, the following realistic charged lepton masses are obtained, $m_e \simeq 0.511$ MeV, $m_\mu \simeq 105.6$ MeV and $m_\tau \simeq 1.77$ GeV. We note that even if $a \neq b$, the matrices C_L , C_e and Y_e can all still be diagonalized simultaneously and thus avoid the tree-level FCNCs.

Massive neutrino case. To accommodate massive neutrinos and lepton mixing, we introduce three right-handed (RH) neutrinos in

the model. The RH neutrinos reside in different $SU(2)_R$ doublets [6] from those that contain the iso-spin singlet charged leptons. The RH neutrinos couple to the lepton doublets to form Dirac mass terms through the Yukawa coupling Y_ν . The relevant Lagrangian in this case is given by³

$$\mathcal{L}_{5D}^{\text{lep}} \supset \bar{L} C_L L + \bar{e} C_e e + \bar{N} C_N N + \bar{H} \bar{L} Y_e e + \bar{H} \bar{L} Y_\nu N. \quad (4)$$

The smallness of neutrino masses is then archived by localizing the RH neutrinos close to the Planck brane such that their overlap with the lepton doublets is small.

With the MFV assumption, the 5D bulk mass matrices are related to the 5D Yukawa couplings as

$$C_e = a Y_e^\dagger Y_e, \quad C_N = d Y_\nu^\dagger Y_\nu, \quad C_L = c (\xi Y_\nu Y_\nu^\dagger + Y_e Y_e^\dagger), \quad (5)$$

where a, d, c are $\mathcal{O}(1)$ parameters and C_N is the bulk mass term for the RH neutrinos. With three RH neutrinos, the global flavor symmetry is $U(3)_L \times U(3)_e \times U(3)_N$, with which one can rotate to a basis where either Y_e or Y_ν is diagonal. In the following analysis, we work in the basis in which Y_e is diagonal and it is denoted by \hat{Y}_e . In this basis, Y_ν can be written as $Y_\nu = V_{5D} \hat{Y}_\nu$, where V_{5D} is the 5D leptonic mixing matrix. All flavor mixing in the lepton sector are generated by V_{5D} . In this basis, both C_e and C_N are diagonal. However, due to the term which is proportional to the parameter ξ , the 5D bulk mass matrix C_L is not diagonal and it can be written as,

$$C_L \simeq (\xi V_{5D} \hat{C}_N V_{5D}^\dagger + \hat{C}_e), \quad (6)$$

where $\hat{C}_N \equiv d \hat{Y}_\nu \hat{Y}_\nu^\dagger$ and $\hat{C}_e \equiv a \hat{Y}_e \hat{Y}_e^\dagger$ are diagonal. To get Eq. (6), we have assumed $a \simeq c \simeq d$. The eigenvalues of C_L give the zero mode localizations of the $SU(2)_L$ doublets along the fifth dimension. Eq. (6), which results from the MFV assumption, leads to a set of conditions that constrain the 5D bulk mass parameters.

The non-diagonal term in Eq. (6) is the source of the FCNCs in the charged lepton sector. Because this term is proportional to ξ , the size of the contributions to FCNCs is thus determined by the value of ξ , which turns out to be small in order to accommodate realistic lepton masses, as we show below. Because Eq. (6) involves the unknown mixing matrix V_{5D} , to estimate the value of ξ , we take the trace on both sides of Eq. (6)

$$\text{Tr}(C_L) \simeq c (\xi \text{Tr}(C_N) + \text{Tr}(C_e)), \quad (7)$$

where we have replaced $\hat{C}_{N,e}$ with $C_{N,e}$ as trace is invariant under the basis transformation. To get realistic charged lepton masses, c_{L_i} and c_{e_i} are in the range of (0.4–0.6). To accommodate small neutrino masses, the RH neutrinos must be localized near the Planck brane, and thus c_{N_i} are in the range of (1.2–1.5). To satisfy the conditions in Eq. (6), ξ must be in the range of (0–0.1). As a result, all FCNCs mediated by $(V-A) \times (V+A)$ type operators in the charged lepton sector are suppressed by a factor of $\mathcal{O}(\xi^2) = (0-0.01)$. For $(V-A) \times (V-A)$ operators, the suppression factor is $\mathcal{O}(\xi^4)$. In the limit $\xi = 0$, all tree-level FCNCs vanish and the only sources of flavor violation processes are the charged current interactions as in the SM.⁴ When $\xi \neq 0$, non-diagonal C_L causes tree-level FCNCs. This is sometimes referred to as the “next to minimal flavor violation” (NMFV).

³ Here we implicitly assume lepton number conservation so that no Majorana mass term $LLHH$ is generated.

⁴ Similar to the massless neutrino case discussed before, the higher order corrections involving four or more Yukawa couplings to Eq. (5) could be important. In particular, the term $Y_e Y_e^\dagger Y_\nu Y_\nu^\dagger$ could potentially lead to sizable flavor violation even for vanishing ξ . Nevertheless, from the numerical example given below, the Yukawa couplings are smaller compared to 1 and therefore we keep only leading-order terms.

¹ For simplicity, we omit flavor symmetry invariant identity contributions to the 5D mass parameters. Including these terms does not change our conclusions.

² In our numerical study, we assume the brane Higgs limit. Our results can be easily extended to the bulk Higgs case [18].

The connection between small neutrino masses and the strong suppression of FCNCs appears at first to depend crucially on the assumption that $c \gtrsim d$. As it turns out, small neutrino masses still implies small ξ , even for $c < d$. This is because by increasing d , the 5D Yukawa Y_ν has to decrease to get the right neutrino masses. In this case, the suppression of FCNCs is due to the small Yukawa couplings, which is again required by the smallness of the neutrino masses. Note that in the limit $Y_\nu \rightarrow 0$, there is no FCNCs in the case with MFV assumption.

Even though the FCNC processes are suppressed due to the MFV assumption, the MFV assumption does not suppress flavor violation in the charged currents. In the presence of massive neutrinos, there are new contributions to the rare decays $\ell_\alpha \rightarrow \ell_\beta + \gamma$, due to the charged current interactions involving the exchange of KK W-bosons and KK neutrinos. The zero mode contributions are suppressed by the GIM mechanism. However, the contributions of the KK gauge bosons and KK neutrinos invalidate the conditions required by the GIM mechanism, because of the heavy masses of the KK neutrinos and the fact that the 4D effective mixing matrix is not unitary. It has been shown that if the relevant entries in the 5D Dirac Yukawa matrix are of order unity without the assumption of MFV, the most stringent constraint, which is from $\text{BR}(\mu \rightarrow e\gamma)$, requires the first KK mass scale to be $\gtrsim 25$ TeV, assuming all SM fields are localized on the TeV brane and only the RH neutrinos are in the bulk [11]. In the case with all fermions and gauge bosons in the bulk while Higgs is localized on the TeV brane, this bound can be relaxed: with $\mathcal{O}(1)$ Yukawa coupling, the bound on the first KK mass scale is ~ 6.7 TeV, and it can be further relaxed in the bulk Higgs case.⁵ One way to keep the first KK mass scale accessible to the LHC while avoiding the $\mu \rightarrow e\gamma$ constraint is to tune the elements of the 5D Yukawa coupling. We comment that this is possible with our MFV assumption, which ensures the contributions to FCNCs are under control. However, in the case with general anarchical flavor structure in the lepton sector without MFV assumption, the constraint on the first KK mass cannot be loosened by tuning the Yukawa couplings, due to the opposite dependence on the Yukawa couplings in the FCNC contributions.

For simplicity, we do not include CP violation in our numerical results. In this case, the 5D bulk masses and the leptonic Yukawa sector are determined by only 12 independent physical parameters. This is to be compared with the generic anarchy case, in which the number of independent parameters is 27. We show below that with 12 parameters, we are still able to find solutions that give rise to all realistic lepton masses and mixing angles, even in the presence of the constraint given by Eq. (6). In the general case with small but not-vanished ξ , C_L is not in the diagonal form. The resulting coupled equations are complicated to solve. For simplicity, we give a numerical example with $\xi = 0$. In this limit, all FCNCs vanish. We leave the possibility of having $\xi \neq 0$ for further investigation.

With $\xi = 0$, all three matrices, C_L , C_e and Y_e , can be diagonalized simultaneously. Realistic charged fermion masses arise with $Y_{e1} \simeq 0.405$, $Y_{e2} \simeq 0.375$ and $Y_{e3} \simeq 0.354$, assuming $a = c = d = 4$. Because the 5D charged fermion Yukawa matrix is diagonal, the 4D effective PMNS matrix is determined entirely by the neutrino sector. In our model, the light neutrino masses are generated by the Dirac Yukawa couplings, $m_\nu \simeq v F_L V_{5D} \hat{Y}_\nu F_N$, where the eigenvalues of F_L and F_N are given by

$$f_{L_i} = \sqrt{\frac{1 - 2c_{L_i}}{1 - \epsilon^{1-2c_{L_i}}}}, \quad f_{N_i} = \sqrt{\frac{1 - 2c_{N_i}}{1 - \epsilon^{1-2c_{N_i}}}} \quad (8)$$

and c_{L_i} and c_{N_i} are the eigenvalues of C_L and C_N .

We choose the following 5D parameters as inputs: $\theta_{12} \simeq 1.383$, $\theta_{23} \simeq 1.358$, $\theta_{13} \simeq 1.338$, $Y_{\nu 1} \simeq 0.713$, $Y_{\nu 2} \simeq 0.5634$ and $Y_{\nu 3} \simeq 0.5475$, where $\hat{Y}_\nu = \text{diag}(Y_{\nu 1}, Y_{\nu 2}, Y_{\nu 3})$ and $\theta_{1,2,3}$ are the three angles that parametrize the 5D mixing matrix V_{5D} . The 5D Dirac Yukawa coupling matrix is

$$Y_\nu \equiv V_{5D} \hat{Y}_\nu \simeq \begin{pmatrix} 0.0307 & 0.128 & 0.533 \\ -0.275 & -0.504 & 0.123 \\ 0.657 & -0.217 & 0.0267 \end{pmatrix}. \quad (9)$$

With these 5D parameters, the effective 4D neutrino oscillation parameters are

$$\sin^2 \theta_{12}^\nu \simeq 0.28, \quad \sin^2 \theta_{23}^\nu \simeq 0.49, \quad \sin^2 \theta_{13}^\nu \simeq 0.023, \\ \Delta m_{21}^2 \simeq 7.4 \times 10^{-5} \text{ eV}^2, \quad \Delta m_{31}^2 \simeq 2.7 \times 10^{-3} \text{ eV}^2, \quad (10)$$

which are in good agreement with experiments within 2σ [19]. Here we assume a slightly large value of $d = 4$ such that the magnitudes of the 5D Dirac Yukawa couplings are small. As a consequence, $\mu \rightarrow e\gamma$ mediated by the heavy neutrinos is suppressed. We estimate the branching fraction $\text{Br}(\mu \rightarrow e\gamma)$ to be $\sim 10^{-12}$, induced by charged current interactions, with the first KK mass scale ~ 3 TeV.⁶ The branching fraction can be further suppressed by tuning the 5D Yukawa couplings and having the Higgs in the bulk.

Even though the eigenvalues of Y_ν are of the same order $\sim \mathcal{O}(0.5-0.7)$ and 5D mixing angles are $\sim \mathcal{O}(1)$, Y_ν given in Eq. (9) deviates from the generic anarchical case with the largest ratio between two elements being $\mathcal{O}(25)$. This deviation is required to give realistic neutrino mixing and masses in the case of $\xi \simeq 0$, in which all FCNCs vanish. The reason is the following: in the generic anarchical case, the left-handed mixing are given by $V_{ij} \sim f_{L_i}/f_{L_j}$, and the large solar and atmospheric neutrino mixing angles requires $f_{L_1}/f_{L_2} \sim 1$ and $f_{L_2}/f_{L_3} \sim 1$. However, in the MFV case with $\xi = 0$, f_{L_i}/f_{L_j} is fixed by $\sqrt{m_i/m_j}$ and thus $f_{L_1}/f_{L_2} \simeq 0.07$ and $f_{L_2}/f_{L_3} \simeq 0.24$. To accommodate these ratios as well as large mixing angles simultaneously, some structure in the 5D Yukawa couplings is thus needed.⁷ It would be appealing to see if the model can accommodate $f_{L_1}/f_{L_2} \sim 1$ and $f_{L_2}/f_{L_3} \sim 1$ in the presence of small but non-vanishing ξ , which may lead to interesting predictions for tree-level lepton flavor violation processes.

3. Conclusions

We propose a realization of Minimal Flavor Violation in the lepton sector of the RS model. With the MFV assumption, the only source of flavor violation are the 5D Yukawa couplings, and the usual two independent sources of flavor violation are now related. In the limit of massless neutrinos, there exists a basis in which the bulk mass matrices and 5D Yukawa matrices are simultaneously diagonalized, and thus there is no tree level FCNCs. In the case of massive neutrinos, the contributions to FCNCs in the charged lepton sector are highly suppressed, as a result of the smallness of neutrino masses. Even though, the MFV mechanism does not suppress the flavor changing charged-current contributions mediated by KK neutrinos, it nevertheless allows the possibility of tuning the 5D Yukawa couplings to suppress these contributions, which is not possible in the generic anarchical case due to the opposite dependence on the Yukawa couplings between the tree-level FCNC and one-loop charged current contributions. We find that the first KK

⁶ In general, there could be UV-sensitive one-loop contributions on the IR brane that lead to $\mu \rightarrow e$ conversion. From our estimate, these contributions are of the order of $\lesssim \mathcal{O}(10^{-20})$ for KK mass ~ 3 TeV. Therefore, the bound on the cutoff scale derived from these contributions is less stringent compared to the limit derived from $\mu \rightarrow e\gamma$ [13].

⁷ In the generic anarchical case, one would expect large θ_{13}^ν comparable to θ_{12}^ν , unless there exists some accidental cancellation.

⁵ We thank K. Agashe for pointing this out to us.

mass scale as low as ~ 3 TeV can be allowed. In both cases with either massless or massive neutrinos, we have found numerical results that give rise to realistic lepton masses and mixing angles, including those for the neutrinos.

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